Microwave Properties of Diluted Composites Made of Magnetic Wires With Giant Magneto-Impedance Effect

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***Abstract*—Free space permittivity measurements are presented on lattices of magnetic microwires . It is shown that the magnetic properties strongly affect the dielectric response of the composite. A model is presented, that accounts for these observations. The microwave dielectric function is shown to depend on the microwave impedance of the wire. Previous works on giant magneto impedance have provided a strong theoretical and experimental background, that may now be used to design composites with complex dielectric response, and also tuneable response. Some principles for making tuneable composites are presented, and illustrated by experimental results.**

***Index Terms*—Giant magneto impedance, microwave, microwires, negative index, tuneable permittivity, wire medium.**

I. Introduction

THE possibility of engineering microwave composites with new and attractive properties has attracted considerable attention, since the pioneering work of Pendry [1] and Smith [2] on composites with negative index of refraction. These composites have a negative refraction index due to a negative permeability and permittivity. They are denominated either left-handed materials, negative index materials or metamaterials. The negative permittivity properties are commonly achieved through a wire media consisting of an array of conducting wires. Though negative real permeability is commonly observed in magnetic materials [3], the microwave permeability can be engineered using non magnetic materials. Conducting loops [4] or other kind of inductive patterns [5] can lead to sharp permeability resonance, with negative real permeability above the resonance frequency.

So, if the permeability that is commonly associated with magnetic materials can be engineered to some extent with non magnetic materials, one may wonder if the permittivity, which is commonly associated with electrical properties, can be engineered using magnetic materials.

Indeed, the conduction properties of ferromagnetic materials have been thoroughly investigated in the microwave range in recent years. In particular, it has been shown that high frequency currents flowing trough magnetic wires [6] or ribbons are significantly affected by the magnetic properties of the conductor, as a consequence of skin effect. Therefore, the impedance of a given length of conductor can be drastically affected by an external magnetic field. This effect has been called the Giant Magneto Impedance Effect. This effect is well documented, and as a consequence the conduction properties are well known for a variety of wires [7] and ribbons [8] of various dimensions, types, and magnetic properties. It is known that the high frequency impedance is affected not only by a parallel magnetic field, but also by stress, torsion, and magnetic fields produced by a current. The GMI properties of materials have been found useful for a variety of applications, especially sensors [9]–[13].

It is very tempting to use the specific electrical properties of ferromagnetic conductors to build composite materials with new types of dielectric responses [14], and to tune this response through a magnetic field, a stress, or a current. The purpose of this work is to give experimental results that support this view, and to provide the theoretical background for the conception of new dielectric materials based on magnetic conductors. In particular, we show that there are two regimes, depending on the wavelength. In one regime, the permittivity of the composite is dominated by the GMI properties of the magnetic inclusions. In the higher frequency regime, the behavior of the composite is hardly affected by the magnetic properties of the conductor. The numerous experimental and theoretical advances related to GMI that have been performed in recent years may therefore be useful to design and build attractive microwave materials with engineered dielectric properties.

II. Experimental Details

A. Amorphous Glass-Coated Ferromagnetic Microwires

Amorphous glass-coated ferromagnetic microwires are compound wires with a very thin metallic magnetic core and a glass outer shell. They are elaborated in our laboratory using the Taylor-Ulitovsky process that allows a wide range of geometric and magnetic characteristics [15]. Ferromagnetic properties are indeed given both by the magnetic properties of the metallic alloy and by the geometric characteristics of the wires. The magnetic structure of the wire is strongly dependent on the sign of the magnetostriction coefficient [16].

For this study, we used FeCoSiB wires with a core diameter around 10 $\mu\mathrm{m}$. The sign of the magnetostriction coefficient was varied by tuning the $\mathrm{Fe}/(\mathrm{Co}+\mathrm{Fe})$ ratio in the alloy. The main characteristics of the wires W1 and W2 that we used here are reported in Table I.

The hysteresis cycles of microwires W1 and W2 are presented in Fig. 1. They were measured at 2 kHz using an inductive specifically designed hysteresis-meter.

Manuscript received December 30, 2002.
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Digital Object Identifier 10.1109/TMAG.2003.816011

TABLE I
MAIN CHARACTERISTICS OF THE SELECTED WIRES: METALLIC CORE DIAMETER DMET, TOTAL DIAMETER DTOT, SATURATION MAGNETIZATION $4\pi M$ AND MAGNETOSTRICTION COEFFICIENT λs

Wires	Dmet (μm)	Dtot (μm)	4πM (kG)	λs
W1	9.5	15	7.5	small positive
W2	10.5	14	6	small negative

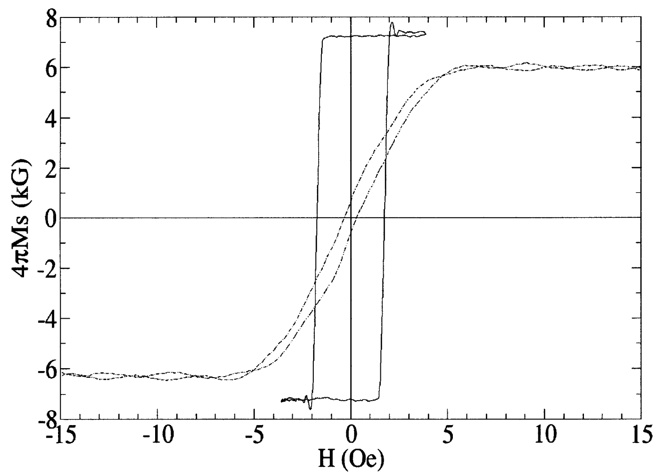

Fig. 1. Hysteresis loops for W1 (full line) and W2 (dashed line).

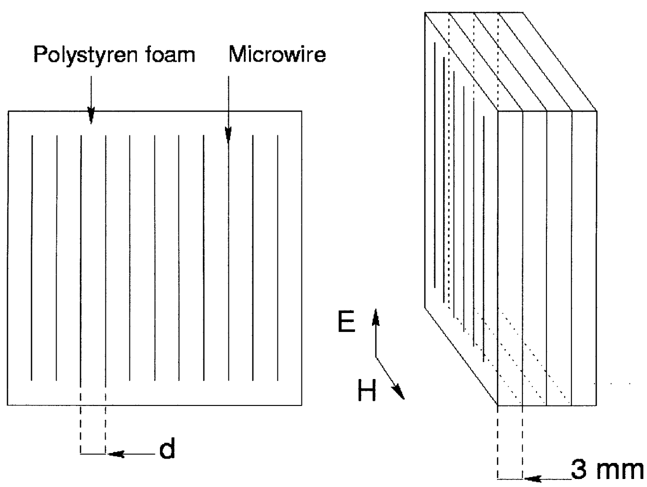

Fig. 2. Lattice of ferromagnetic microwires and polarization of interest.

Square hysteresis loop is typical for positive magnetostriction coefficient for which magnetization is essentially along wire axis. In the case of negative magnetostriction W2 wire, usual flat hysteresis loop is obtained.

B. Free-Space Measurements

Free-space composite is a 2-D wire array. The ideal sample is an assembly of parallel wires regularly separated in space. To give a structure to the sample, we used very low density expanded polystyrene foam sheets. The wires are aligned on a $30 \times 30\ \mathrm{cm}^2$ 3 mm-thick foam sheet and maintained using adhesive tape (see drawing in Fig. 2). At this stage, we did pay attention not to apply mechanical stress to the wires.

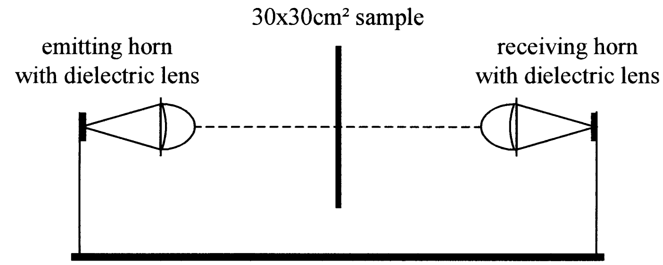

Fig. 3. Free-space measurement setup including sample holder and two 2–18 GHz horns with focalization lenses.

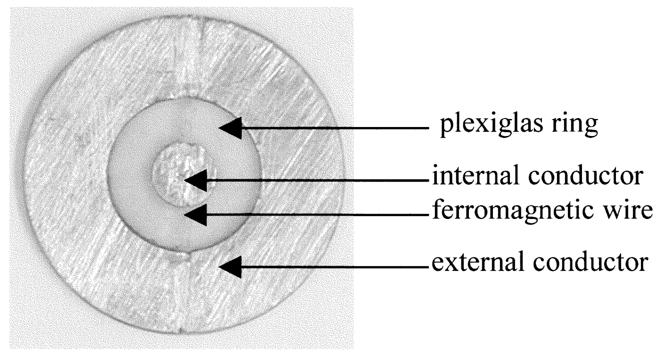

Fig. 4. Coaxial line sample of wire composites.

To obtain a thicker sample, multiple layers may be stacked to give a 2-D–3-D composite. As represented in Fig. 2, the polarization of interest is the one with electric field parallel to the wires.

Permeability and permittivity of the sample are determined using a free-space reflection/transmission measurement. The measurement setup is represented in Fig. 3.

Far field interaction is simulated here using spherical focalized waves. Two dielectric lenses are indeed inserted in front of broadband horns on each side of the sample to insure a limited area of illumination. Reflection from and transmission through the sample are measured. The frequency range in that case is 2 to 18 GHz. A calibration using a perfectly conducting plate instead of the sample is performed. Permeability and permittivity are then calculated from the expressions of reflection and transmission (R/T) on an arbitrary medium in air [17].

For the polarization with the microwave magnetic field parallel to wire axis, the permeability and permittivity are very close to 1, within the 5% measurement error. This is coherent with the very low volume of ferromagnetic material in the sample. Measurements with electric field parallel to the wires lead to permeability close to unity for all samples.

C. Coaxial Line Measurements

The sample for coaxial measurement is a very simple composite constituted by one wire and a dielectric substrate. As illustrated in Fig. 4, this basic composite is placed in an APC7 coaxial line sample holder. The wire is inserted between the internal and external conductors of the coaxial line. In that radial position, the wire is parallel to the electric field in the line (TEM mode). The wire is not electrically connected to the conductors of the line.

The permeability is found to be unity, within measurement errors. This is coherent with the fact that the microwire is normal to the magnetic field and that, as for free space sample, the ferromagnetic volume seen by the magnetic field is very small. Permittivity is found to vary with frequency and magnetic properties of wire, and also with applied external parallel magnetic field.

Indeed, the main advantage of this measurement setup compared to free-space is the ability to easily apply a static magnetic field to the wire. We used Helmoltz coils or an electromagnet connected to a dc power supply. Fields up to 2 kOe can be applied parallel to the wire axis.

III. Theoretical Background

Let us consider a lattice of infinitely long parallel wires in a nonmagnetic matrix with relative permittivity ε_m. We now consider the properties of the composite for a normally incident plane wave, with the electric field parallel to the wires and the magnetic field is perpendicular to the wires. The effective permittivity is defined by

$$\varepsilon_0\varepsilon_{\text{eff}} = \frac{\langle D\rangle_V}{\langle E\rangle_V} \tag{1}$$

where $\langle\rangle_V$ stand for the averaging over the volume of the periodic cell. Let us express the average of the electric induction D over the volume of the periodic cell

$$\langle D\rangle_V = (1-f)\varepsilon_0\varepsilon_m\langle E\rangle_{\text{matrix}} + f\langle D\rangle_{\text{wire}} \tag{2}$$

where f is the volume fraction of wire and $\langle\rangle_{\text{wire}}$ stands for the averaging over the wire. The tangential continuity of E field indicates that $\langle E\rangle_{\text{wire}}$ is smaller or of the same order of magnitude as the average field in the matrix $\langle E\rangle_{\text{matrix}}$. For these diluted composites, $f \ll 1$, and so we have

$$(1-f)\langle E\rangle_{\text{matrix}} = \langle E\rangle_V - f\langle E\rangle_{\text{wire}} \approx \langle E\rangle_V. \tag{3}$$

Here, we see that we need to find the expression of $\langle D\rangle_{\text{wire}}/\langle E\rangle_V$. To highlight the link between the GMI and the negative permittivity phenomenon, let us introduce the current density J_{wire} in the microwire

$$\langle D\rangle_{\text{wire}} = \frac{J_{\text{wire}}}{j\omega} = \frac{\sigma_0 E_{\text{ext}}}{j\omega\frac{Z}{R_{dc}}} \tag{4}$$

where E_{ext} is the electric field at the surface of the wire and σ_0 the conductivity of the wire.

To calculate the average of the electric field, we must take into account two contributions: the incident field and the scattered field by the microwire. The details of the calculations are given in [14]. It gives

$$\langle E\rangle_V = J_{\text{wire}}\left(\frac{Z}{\sigma_0 R_{dc}} + jf\mu_0\omega A\right) \tag{5}$$

where A is an area which depends only on the geometry of the lattice, and Z/R_{dc} the Giant Magneto Impedance. For a 3-D-lattice of spacing d of microwires of radius a, the expression of A is given by [18]

$$A = d^2\ln\left(\frac{d}{a}\right). \tag{6}$$

Finally, the effective permittivity of the composite is found to be

$$\varepsilon_{\text{eff}} = (1-f)\varepsilon_m + f\frac{1}{j\omega\frac{\varepsilon_0}{\sigma_0}\frac{Z}{R_{dc}} - fA\frac{\omega^2}{c_0^2}} \tag{7}$$

where c_0 is the speed of light in the vacuum.

For a microwire, a simple model of GMI is

$$\frac{Z}{R_{dc}} = \frac{ka}{2}\frac{J_0(ka)}{J_1(ka)} \tag{8}$$

where k is the wave vector

$$k = \sqrt{-j\omega\mu_0\mu_\theta\sigma_0} \tag{9}$$

μ_θ stands for the circumferential relative permeability of the microwire, which corresponds to a positive magnetostriction coefficient.

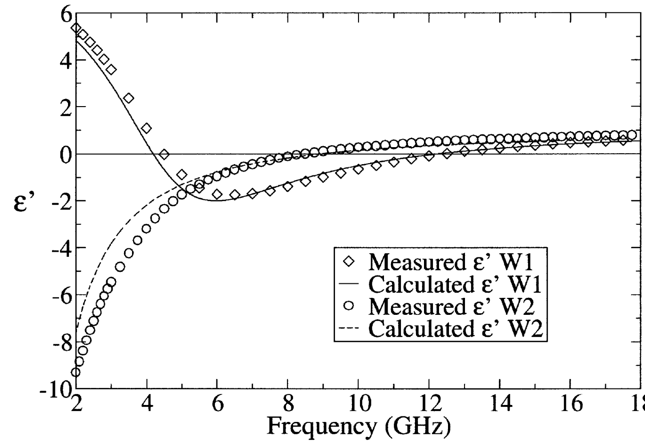

Fig. 5. Measured and calculated real part of the effective permittivity of a lattice of microwires W1 and W2.

IV. Results

Figs. 5 and 6 provide permittivity values on composites obtained from free-space measurements as described in Fig. 3, and is compared to values calculated using the theoretical approach described above. For composites based on W2, with a negative magnetostriction coefficient, the result is the same as the one of a non magnetic metallic wire composite [14]: a "plasmon-like" behavior is observed as in [19]. It is due to the fact that in this polarization the RF magnetic field is parallel to the magnetization of W2. μ_θ has a value close to unity. The microwire W1 has a positive magnetostriction coefficient. For a W1-based composite, a resonance around 4 GHz is measured instead of the plasmon-like behavior. In this case, μ_θ is expected to be large and exhibits significant dispersion. This accounts for the differences between the overall behavior of the two composites.

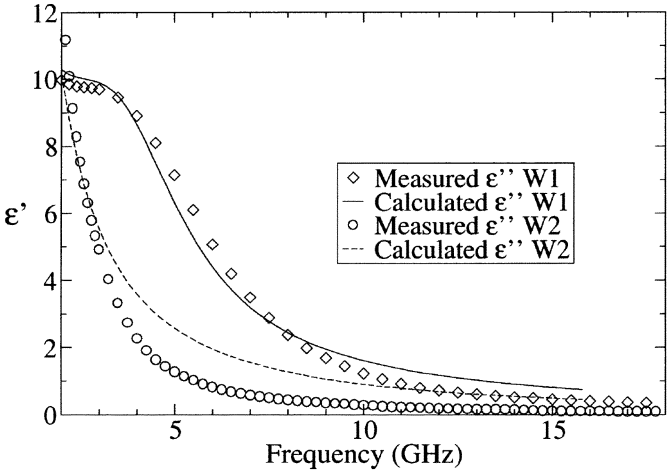

Fig. 6. Measured and calculated imaginary part of the effective permittivity of a lattice of microwires W1 and W2.

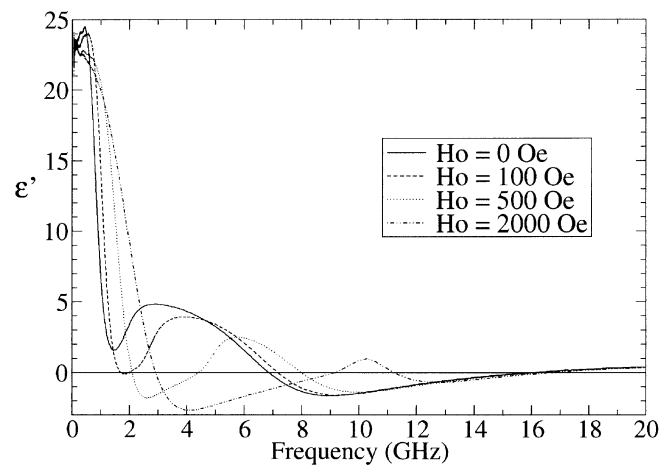

Fig. 7. Real part of the measured effective permittivity in coaxial line of the sample of W1-based composite described in Fig. 4. A static magnetic field is applied parallel to the axis of the microwire W1.

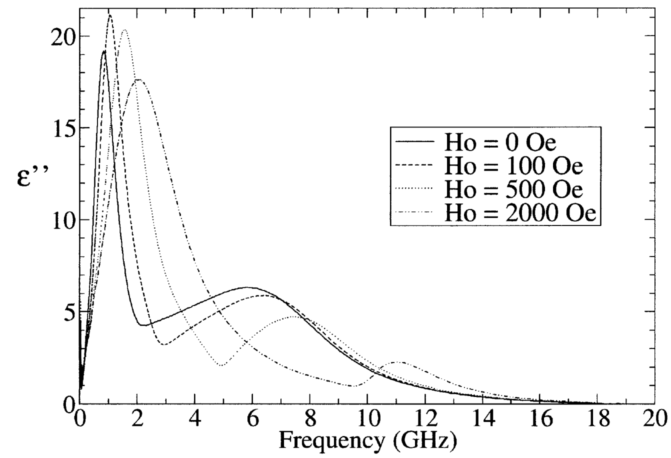

Fig. 8. Imaginary part of the measured effective permittivity in coaxial line of the sample of a W1-based composite described in Fig. 4. A static magnetic field is applied parallel to the axis of the microwire W1.

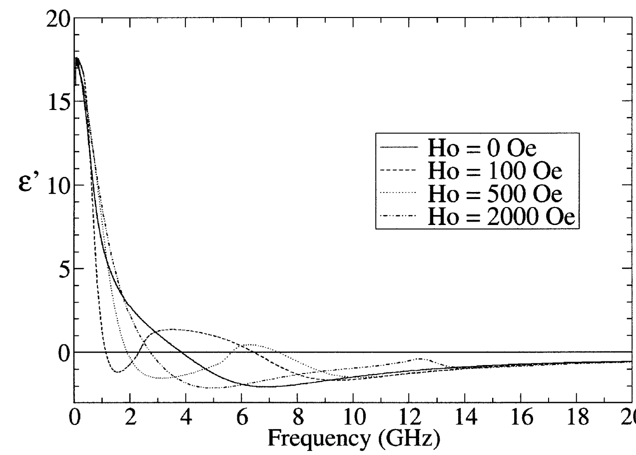

Fig. 9. Real part of the measured effective permittivity in coaxial line of the sample of W2-based composite described in Fig. 4. A static magnetic field is applied parallel to the axis of the microwire W2.

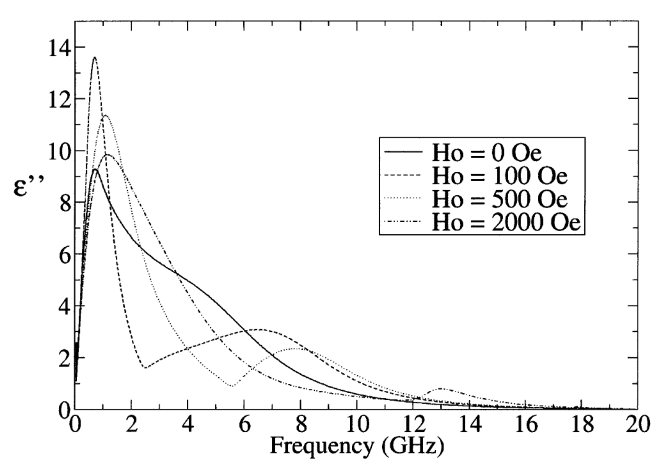

Fig. 10. Imaginary part of the measured effective permittivity in coaxial line of the sample of W2-based composite described in Fig. 4. A static magnetic field is applied parallel to the axis of the microwire W2.

A very good agreement is observed for the sample W2 between the measured permittivity, and the permittivity obtained from (7)–(9) with $\mu_\theta = 1$.

For W1, the circumferential permeability of the axially magnetized microwire may be described in a first approach by the Gilbert model. For acceptable values of the anisotropy field H_a and the damping parameter α [14], the permeability of the Gilbert model inserted in (7)–(9) yields also an excellent agreement for the W1 composite.

In Figs. 7 and 8, the results of the measurements in coaxial line are reported for the W1 microwire with positive magnetostriction coefficient. By applying a static magnetic field parallel to the microwire, the direction of the magnetization is changed from mainly axial to totally axial, and this affects μ_θ and Z. This is well known from GMI experiments. This accounts for the significant evolution of the permittivity of the W1-composite with the applied magnetic field. It is clear in Fig. 7 that the permittivity becomes negative over large frequency bands.

Figs. 9 and 10 show the results of measurements in coaxial line of sample of a W2-based composite. A static magnetic field has been applied parallel to the axis of the wire. The magnetization of the wire W2 is mainly circumferential at 0 Oe. But the static magnetic field reorients it to a mainly axial magnetization. All the magnetic structure of the wire is then modified. This affects the circumferential permeability, the impedance, and therefore the permittivity, according to (7)–(9).

It should be notice that the shapes of the permittivity in Figs. 5 and 7 are not identical. Indeed, the two experiments are not rigorously equivalent. In the coaxial experiment, the system behaves more like interacting dipoles, as if the infinitely long wires had been cut. It is due to the fact that there is no electrical contact between the coaxial line and the microwire. This accounts for the positive permittivity observed at low frequencies. Nevertheless, the resonance due to GMI is observed, though its frequency is affected.

V. Discussion

These ferromagnetic composites exhibit a new type of dielectric response which can be controlled by a static magnetic field. Focusing our mind on (8), two regimes may easily be spotted in order to describe the mechanism of the effective permittivity in lattices of microwires.

The first is located at low frequencies. In this regime, (7) reduces to

$$\varepsilon_{\text{eff}} = (1-f)\varepsilon_m - f\frac{j\sigma}{\omega\varepsilon_0}\frac{R_{dc}}{Z}. \tag{10}$$

The permittivity is clearly associated with the GMI effect, which is dominant.

The second regime appears at high frequencies. The addition of magnetic properties does not affect the effective permittivity anymore since its expression reduces to

$$\varepsilon_{\text{eff}} = (1-f)\varepsilon_m - \frac{c_0^2}{A\omega^2}. \tag{11}$$

This expression of the permittivity is only dependent on the geometry, in accordance with previous works on lattices of nonmagnetic metallic wires with strong skin effect [20], [21]. In the present approach, the dielectric function has been computed from the definition given by (1). On the other hand, it is well known that effective medium theories (EMT) are generally successful in describing the electromagnetic properties of composite materials. One may wonder how this approach compares to the present results. In the case of a composite medium with all the inclusions parallel to the electric field, both Maxwell Garnett and Bruggeman models simplify into a simple dilution law

$$\varepsilon_{\text{eff}} = (1-f)\varepsilon_m + f\varepsilon_{\text{inclusion}}. \tag{12}$$

A straightforward proof of (12) can be found in [22]. This holds provided the lateral dimensions of the inclusions are much smaller than the wavelength in the inclusions. For the wire media under investigation, it requires in particular that the skin effect is negligible in the wires, or in other words that R_{dc}/Z is close to unity. Then, using the permittivity of a metal $\varepsilon = -j\sigma/(\omega\varepsilon_0)$ in (12), the prediction of the EMT is

$$\varepsilon_{\text{eff}} = (1-f)\varepsilon_m - f\frac{j\sigma}{\omega\varepsilon_0}. \tag{13}$$

This expression is equivalent to (10) in the case $R_{dc}/Z = 1$ under consideration.

It is known that EMT can be extended to the case of metallic inclusions with skin effect, provided that the polarizability of the inclusion is calculated taking into account the non uniformity of the field in the inclusion. This has been successfully applied especially to the permeability of materials [23]. In the present case, one should plug into (12) instead of the intrinsic permittivity of the metal the quantity

$$\frac{\langle D\rangle_{\text{wire}}}{\varepsilon_0 E_{\text{ext}}} = -j\frac{\sigma_0}{\omega\varepsilon_0}\frac{R_{dc}}{Z}. \tag{14}$$

By doing that, one obtains (10), which therefore appears to be the prediction of the permittivity of the composite obtained from extended EMT's. R_{dc}/Z being a complex number, this introduces a significant rotation of the argument of the permittivity compared to the quasistatic EMT approach. In particular, it accounts for the large negative ϵ' observed on Fig. 5.

The difference between the EMT prediction (10), and the complete formula (7), is due to inhomogeneities in the fields in the matrix, though it has a low index. The field inhomogeneity due to currents not taken into account in conventional EMT.

Several other features of the wire media may be mentioned: diffraction effects exist for higher frequencies [24], as it can be seen in Fig. 3 of [14]. Spatial dispersion should also be taken into account in some cases [21].

We have shown experimentally that composites with a permittivity tuneable under a magnetic field can be obtained. Our results obtained in coaxial line on single-wire composites can be extended to larger size composites and other measurement configurations. A variety of topologies, such as arrays of ribbons, fibers [4], or wire, with one dimension of the order of the skin depth, can be designed. Amorphous glass coated microwires are well suited to build tuneable composites, since the various ways for tailoring the magnetic properties aimed at maximizing the GMI effect have been extensively studied: composition, magnetostriction, process conditions, heat annealing, Joule annealing, stress annealing, and combinations of these conditions [25], [26]. High-frequency GMI measurement setups [27], [28] may give our approach a useful support, and illustrate more precisely the two working modes discussed above.

VI. Conclusion

Arrays of magnetic microwires may be attractive to design microwave composites with engineered permittivity response. We proposed a model that accounts for the properties of such composites over a wide frequency range. We show that the underlying physics of these materials has some strong connection with that of GMI. As a consequence, the scientific background on GMI may be very useful to manufacture smart microwave materials.

Acknowledgment

The authors would like to thank K. Poliakoff and J.-H. Le Gallou for the measurements.

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